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5G Technologies for the Connected Car

Mikael Fallgren, Markus Dillinger, Jesus Alonso-Zarate, Mate Boban, Taimoor Abbas, Konstantinos Manolakis, Toktam Mahmoodi, Tommy Svensson, Andres Laya, Ricard Vilalta

***Abstract*—This paper discusses the role of 5G technologies for the connected car. 5G technologies will enable cars and vehicles to be connected to the networks and also to be able to talk to each other ensuring ultra high reliability and very low latency. Enabling such kind of connectivity will leverage disruptive new applications that will allow to improve driving efficiency and boost road safety. First preliminary results from the EC-funded 5GPPP 5GCAR project are presented with regard to certain technologies that will enable the connected car, including channel measurement and modeling, advanced V2X communications, and fog computing. Also, a business perspective is provided, where the transformation of the automotive sector due to 5G is discussed.**

***Index Terms*—Connected car, 5G, V2X, channel measurements, cellular, fog computing, business ecosystem, automotive sector transformation.**

I. INTRODUCTION

Two strong technology trends, one in the mobile communications industry and one in the automotive industry, are becoming interwoven and will jointly provide new capabilities and functionality for upcoming intelligent transport systems (ITS) and future driving.

The automotive industry is on a path where vehicles are continuously becoming more aware of their environment due to the addition of various types of integrated sensors. At the same time, the amount of automation in vehicles increases, which – with some intermediate steps – will eventually culminate in fully-automated driving without human intervention. Along this path, the amount of interactions increases, both in-between vehicles, between vehicles and other road users, and with an increasingly intelligent road infrastructure. As a consequence, the significance and reliance on capable communication systems for vehicle-to-anything (V2X) communication is becoming a key asset that will enhance the performance of automated driving and increase further road traffic safety with combination of sensor-based technologies.

On the other hand, the mobile communications industry has over the last 25 years connected more than 5 billion people and mobile phones have become part of our daily living. The next step in wireless connectivity is to connect all kinds of devices that can benefit from being connected, with a total of 28 billion connected devices predicted until 2021.

M. Fallgren and A. Laya are with Ericsson, Sweden.
M. Dillinger, M. Boban, and K. Manolakis are with Huawei German Research Center, Germany.
J. Alonso-Zarate and R. Vilalta are with Centre Tecnologic de Telecomunicacions de Catalunya (CTTC/CERCA).
T. Abbas is with Volvo cars, Sweden.
T. Mahmoodi is with Kings College London, UK.
T. Svensson is with Chalmers University of Technology, Sweden.
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II. THE 5GCAR PROJECT

5GCAR project, which is a 5G PPP Phase 2 project, brings together a consortium from the automotive industry, the mobile communications industry, and academia. The goal of the project is to develop technologies at the intersection of automotive and mobile communication sectors in order to support a fast and successful path towards safer and more efficient future driving. The key objectives of 5GCAR are to reduce end-to-end latency, improve reliability, ensure high availability, guarantee interoperability of heterogeneous radio technologies, increase scalability (massive access), and secure vehicular communications. Figure 1 illustrates the 5GCAR concept and its key technical components.

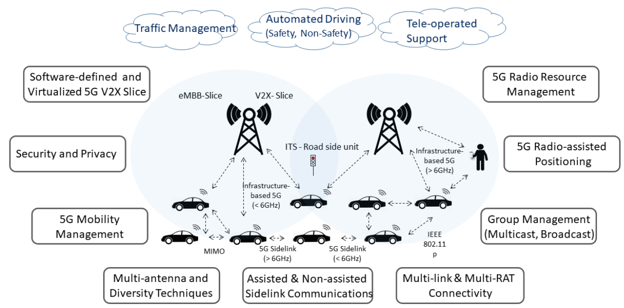


Fig. 1: The 5GCAR concept and its key technical components

The main objectives of the 5GCAR project are:

- Develop an overall 5G system architecture providing optimized end-to-end V2X network connectivity for highly reliable and low-latency V2X services, which supports security and privacy, manages quality-of-service and provides traffic flow management in a multiple Radio Access Technology (multi-RAT) and multi-link V2X communication system.
- Interworking of multi-RATs that allows embedding existing communication solutions (including short range technologies) and novel 5G V2X solutions.
- Develop an efficient, secure and scalable side-link interface for low-latency, high-reliability V2X communications leveraging 3GPP solutions.
- Propose 5G radio-assisted positioning techniques for both Vulnerable Road Users (VRUs) and vehicles to increase the availability of very accurate localization.
- Identify innovative business models and spectrum usage alternatives that support a wide range of 5G V2X services, which drive the functional design of the 5G V2X architecture.

- Demonstrate and validate the developed concepts and evaluate the quantitative benefits of 5G V2X solutions using highly and fully automated driving scenarios in test sites.
- Contribute to 5G standardization and regulatory bodies and 5G Automotive Association for enabling radio-supported and automated driving solutions.
- Collaborate and integrate the 5G V2X radio access network concepts of the 5GCAR project into the overall 5G Radio Access Network (RAN) framework, through participation in the 5G PPP initiatives and events and interaction with other projects.

In the remainder of the paper, we discuss a selected set of topics that are necessary for achieving the objectives listed above. Specifically, in Section III we discuss the characteristics of the underlying V2X channels. Section IV discusses the main building blocks of cellular V2X solution, along with detailing the needs in terms of synchronization. Section V argues that flexible network architecture is needed to support advanced V2X services, whereas Section VI explores the potential of using vehicles in the form of mobile base stations as part of that flexible architecture. Section VII discusses fog computing in the context of the connected car, followed by business ecosystem surrounding connected cars in Section VIII. Section IX concludes the paper.

III. V2X CHANNEL MEASUREMENTS AND MODELING

The propagation channel is one of the key performance factors that impacts any communication system. High speed of the vehicles, dynamic surroundings often cluttered with static and mobile scatterers, and low antenna heights create challenges for V2X communications that are unique compared to other communication systems. Furthermore, the variety of applications envisioned that the 5G V2X system aims to support – ranging from basic safety applications [1], to high-precision radio positioning, to advanced cooperative automated driving applications (e.g., platooning, cooperative intersection control, etc.) – results in considerably different requirements in terms of channel modeling.

Several V2X-specific channel models have been developed covering dozens of scenarios and environments based on analytical as well as empirical data analysis. Two recent surveys of these models are available in [2] and [3]. Given the number of scenarios, environments, and classification of models w.r.t. modeling approaches (Fig. 2), there can be hundreds of combinations, which makes it difficult to do a right selection of model parameters. The channel models in context of wireless system design are often used to perform the sensitivity or benchmarking of the chipsets, to gather performance statistics and to test protocol applications while simulating end-to-end system performance. A detailed recipe, which could guide the system designers to be able to choose appropriate V2X channel model is not explicitly available in the literature. Towards providing such a recipe, this section summarizes the key ingredients for selecting appropriate channel models, which are a starting point for a more detailed classification, gap analysis, and further measurements and modeling that will be performed within the 5GCAR project.

We summarize the key components required for correct parametrization of V2X channels in Fig. 2. V2X communication is diverse in terms of both environments where it occurs as well as the type of actors involved in the communication (cf. top of Fig. 2). Therefore, the measurements and model parameterization need to take into account the proper environment (e.g., highway, rural, urban), as well as the link type (vehicle-to-vehicle -V2V-, Vehicle-to-Infrastructure -V2I-, Vehicle-to-Pedestrian -V2P-).

Next, the dimensions of vehicles and the location of antennas on them have a profound effect on the resulting channel: a channel between roof-mounted antennas on two suburban utility vehicles (SUVs) will be considerably different than a channel between two bumper-level antennas on two personal cars.

Once the link type and antenna locations have been selected and depending on the target application and the target performance metric, channel models can be classified as follows.

1) **Non-geometry based stochastic (NGS)** models are based on statistics extracted from a set of representative measurements for a given environment. They are simple to use and computationally inexpensive. NGS models will typically apply for a specific propagation condition (e.g., line-of-sight -LOS-) and will either not incorporate or provide abstracted versions of more detailed mechanisms, such as correlated fading, spatio-temporal dependencies, LOS blockage, etc. **Tap-delay line models [4]**, a subgroup of non-geometry based stochastic models, are useful when performing sensitivity testing or benchmarking of the wireless chipsets. They can be easily implemented in channel emulators.
2) **Geometry based deterministic (GBD) and geometry based deterministic stochastic (GBS) models** can be used to evaluate performance of link level protocols, for analyzing network topology statistics, performance of protocols, or end-to-end application testing. Depending on the simulation scale and propagation mechanisms implemented, they are typically classified as link-level or system-level models [4]. Link-level models are mostly concerned with small scale fading required to evaluate link level performance, whereas they abstract away the large scale fading effects. On the other hand, system-level models focus on large scale evaluation and often abstract the small scale aspects through link-to-system mapping.
   Most prominent examples of GBD models are based on ray tracing/ray launching, whereas the model adopted by 3GPP [4], based on evolution of the WINNER framework, is the most often used GBD model. However, up to now, 3GPP models in [4] do not implement some key V2X features, such as the impact of dual mobility on fast fading parameters (necessary for V2V), they do not consider V2X-specific scenarios (highway, street-level urban, roadside unit-to-Vehicle, V2V), and have not considered V2X-specific antennas.

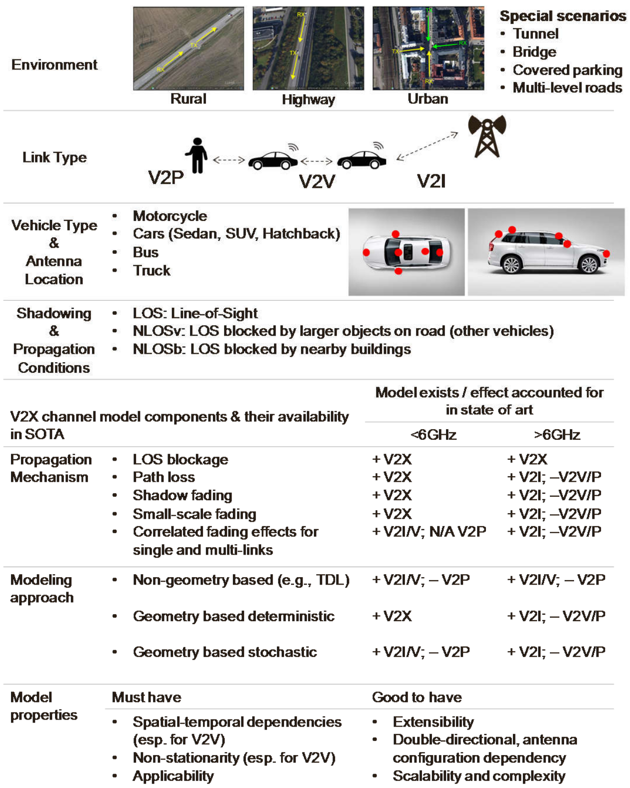


Fig. 2: V2X-specific considerations for channel modeling. For each link type (V2V, V2P, V2I), we indicate whether an appropriate model exists ("+") or not ("-") in the literature. For further details, see [2], [3], [4].

IV. Cellular-based V2X and Synchronization

Cellular-based V2X is considered as the main radio interface to support 5G vehicular communication through three distinct modes, namely *cellular V2X*, *cellular-assisted V2V* and *cellular unassisted V2V*. Cellular V2X refers to "classic" uplink/downlink communication, where a vehicle communicates with a base station or Roadside Unit (RSU). RSUs will be deployed to improve coverage and throughput, as well as to reduce latency through fast radio access, handover, and coordinated resource allocation. Cellular-assisted V2V is a scheme where the base station coordinates the communication between vehicles by providing control information and instructions to vehicles [1]. This mode is well-suited for extremely low latency and high reliability V2V communication, as the network infrastructure ensures resource availability when requested and time-consuming data transmission over the cellular network is avoided. For some use cases, e.g. platooning and see-through, cellular V2V will provide traffic offloading, as data exchange between users in a certain geographical region can be realized by V2V. Finally, cellular-unassisted V2V is a mode where vehicles communicate without direct assistance from the base station. However, resources are still considered under control of the cellular network. Out-of-coverage users further remain synchronized to the cellular network and follow a common time reference. In this sense, even out of coverage users can be considered as part of the cellular network and their transition to one of the other modes can be very fast. In all three modes, the cellular network controls – to different levels – the data transmission between vehicles, and ensures that their needs in terms of data rate, reliability, and latency are satisfied.

One of the most challenging requirements of cellular-based V2X is *time and frequency synchronization*. Unlike IEEE 802.11p, LTE-based and 5G V2X will require users to be synchronized among each other in order to avoid inter-symbol and inter-carrier interference, which are caused by the misalignment of multi-carrier signals transmitted over the air.

Coexistence of V2V and cellular V2X in one frequency band further needs synchronization of base stations and RSUs, which is in contradiction with the typical scenario of non-synchronized base stations of the same or different network operators. Distribution of a common time reference and agreement among all involved network entities must be achieved before any data communication can be established.

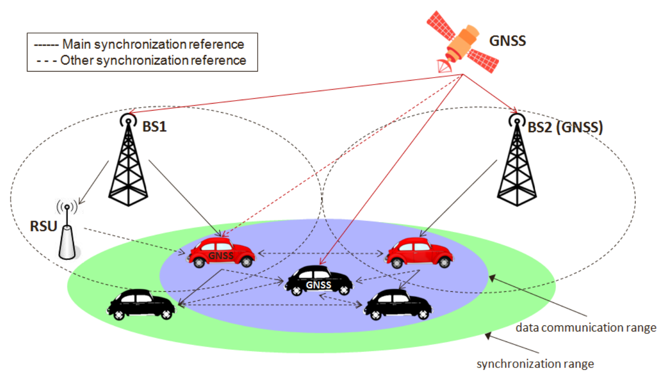


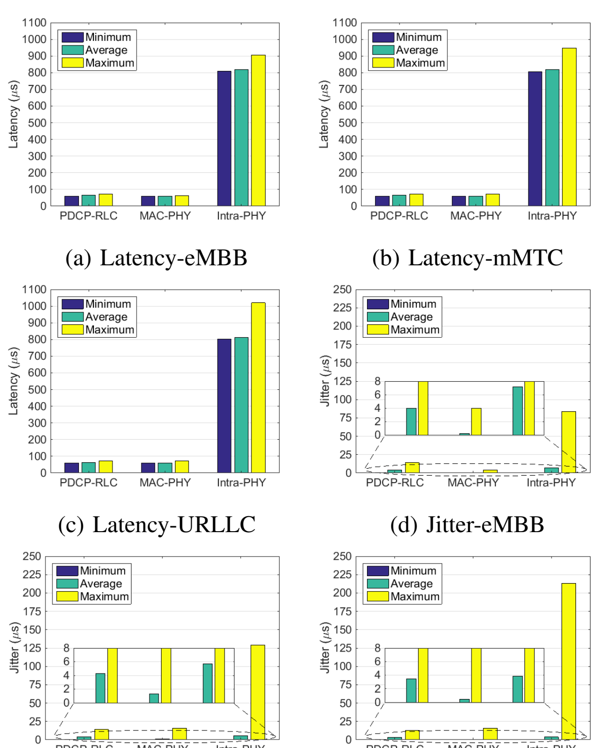
Fig. 3: Scenario with in- and out-of-coverage vehicular users. GNSS may be available to some base stations, RSUs and users. Synchronization source selection and distributed synchronization are used to achieve global synchronization.

Fig. 3 shows a vehicular network with partial cellular coverage. As a design guideline, it is recommended that users pre-synchronize within a larger are than the one for data exchange. In-coverage users follow the time reference provided by their serving base station, whereas out-of-coverage users will have to hierarchically select from available sources such as GNSS or users transmitting synchronization signals in the sidelink. As proposed in [5], source selection and distributed algorithms need to be combined to achieve mutual synchronization. There, it was shown that in a network with 30 users, out of which 10 are in coverage provided by the same base station, 10 with GNSS and 10 obtaining time reference through the sidelink, the proposed mutual synchronization method can reduce the residual timing offset to below 0.5μs, which is smaller than the typical guard interval used for multi-carrier waveforms. The cases of non-synchronized base stations and synchronization between different operators' users need further study, while the design of the sidelink control channel and synchronization sequences will also require careful design for 5G V2X.

V. V2X Radio Access Architecture

Flexible network architecture is envisioned as one of the properties of 5G V2X networks, in order to enable integrated seamless connectivity for multi-RAT, multi-link operation, where ultra-low latency and ultra-high reliability should be supported for critical automotive communications. Such flexibilities can be foreseen in the software-based network control [6], placement of network functionalities [7], and the design of radio access network [8], which then can be realized through network slicing [9]. In this section, we focus on the flexibility in RAN design in terms of how the RAN functionalities can be placed in the fog (details in Section VII), i.e. splitting the radio and baseband functionalities between central cloud and distributed entities.

3GPP has introduced eight options for splitting the functionalities in RAN [10]. Among these options, we examine latency and jitter in the three options of PDCP-RLC, MAC-PHY and intra-PHY (or eCPRI) within an experimental platform, which is further explained in [8] and [11]. The study is performed with traffic models of three classes of service in 5G including URLLC, communication of safety messages, mMTC traffic, representing vehicles' sensors messages, and eMBB traffic, representing infotainment traffic in the vehicle [12]. The ultimate aim of this study is to show which split performs best for which of the application classes in V2X, assuming such split can be achieved in a more dynamic way through SDN and fog computing, further elaborated in the subsequent sections.



(a) Latency-eMBB (b) Latency-mMTC

(c) Latency-URLLC (d) Jitter-eMBB

(e) Jitter-mMTC (f) Jitter-URLLC

Fig. 4: Latency and Jitter for different splits for 5G services (the minimum jitter is equal to 0).

Fig. 4 shows latency and jitter introduced by each split (i.e., the time interval from when a packet transmission is triggered by the upper layer of the split to when the packet is successfully received by the lower layer of the split). We can note that the PDCP-RLC and MAC-PHY splits work in a more stable way compared to Intra-PHY in terms of added latency. In details, the average latency is almost constant for all the splits and equal to $\sim 65\mu s$ for PDCP-RLC and $\sim 60\mu s$ for MAC-PHY. Observing from the jitter plots (Fig. 4-d to Fig. 4-f), the lowest jitter is guaranteed by the MAC-PHY split, as the MAC and PHY layers work in a synchronous way thus reducing the delay variation. Higher jitter is obtained for the PDCP-RLC split, as in this case the PDCP sends a packet to RLC whenever it receives a packets from upper layers with thus higher latency variation. Finally, the highest jitter is obtained with the Intra-PHY split due to the high number of packets (i.e., 14) transmitted every ms.

VI. Integrated Moving Networks

With 5G and its evolutions, users will expect the connected society to be available with no limitations, and users will make use of bandwidth-demanding services like augmented reality and virtual office applications, also when on the move. In this context, future vehicles and transportation systems may play an important role in wireless networks by providing additional communication capabilities and becoming an integrated part of the communication infrastructure to improve capacity and coverage of operator driven mobile networks. That is, in order to serve vehicular users effectively, one promising solution is to deploy moving base stations on the vehicles to form moving networks [13].

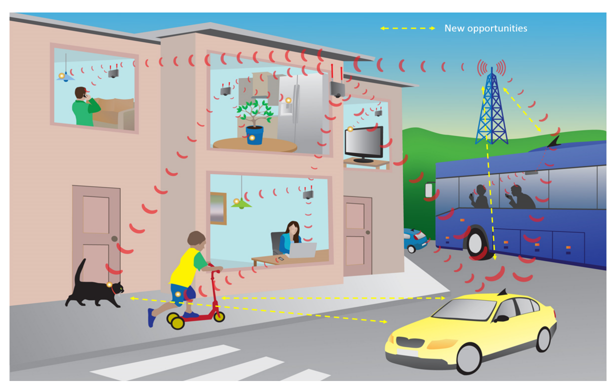


Fig. 5: Illustration of Integrated Moving Networks

One of the purposes of the moving base stations is to effectively serve in-vehicle users, which is becoming more and more demanding for high data rate and low latency services with modern, well insulated vehicles that have a very high penetration loss ($\geq$ 25 dB) in combination with high carrier frequencies ranging up to millimeter-waves ($\leq$ 100 GHz). Yet another important opportunity is to enable moving base stations to act also as cooperative ad-hoc small cell base stations in the heterogeneous mobile networks in order to serve out-of-vehicle users [14].

Thus, there is a large unexplored potential to integrate moving base stations as ad-hoc network elements into the heterogeneous mobile networks with mobile operator controlled network nodes to form integrated moving networks. However, there are also several key open research topics; to name a few: i) tracking a large set of mobile channels at high speed to enable advanced spectrally efficient and robust closed loop (massive) MIMO schemes in the moving backhaul links [15]; ii) designing closed-loop and cooperative interference coordination techniques in ultra-dense heterogeneous networks; iii) resource allocation and resource slicing for versatile QoS services to meet key performance targets on outage, throughput, latency and energy efficiency; and iv) enabling efficient mobility protocols in such integrated moving networks.

Designing such closed-loop cooperative transmission and resource allocation schemes efficiently in hybrid heterogeneous networks consisting of fixed and moving base stations is a challenge. However, there is a vast unexplored potential to take advantage of various kinds of side information, like road infrastructure information, driving route information, positioning, and social networks. By looking into such sources of information, there is also a potential along the way that a lot of new services with associated business models could emerge (more details in Section VIII). Key challenges include handling privacy, security, and implementing authentication and owner protection of these information sources.

Integrated moving networks can also enable ultra-reliable communication links to transport ITS messages between vehicles and mobile devices of so-called vulnerable road users (VRUs), such as pedestrians, cyclists, playing children on the streets, pets , etc., that are not equipped with dedicated communications transceivers for ITS.

Modern vehicles are moving multi-sensor systems that are constantly collecting information. As such, they could be used to support development of smart city applications, such as sensing air quality, road maintenance support, monitoring of noise levels, weather forecasts, traffic congestion levels for route optimization of critical transports, etc. One opportunity that remains to be explored is how municipalities could use this information to optimize the resource efficiency in the cities and to improve quality of life in crowded cities.

VII. FOG COMPUTING AND THE CONNECTED CAR

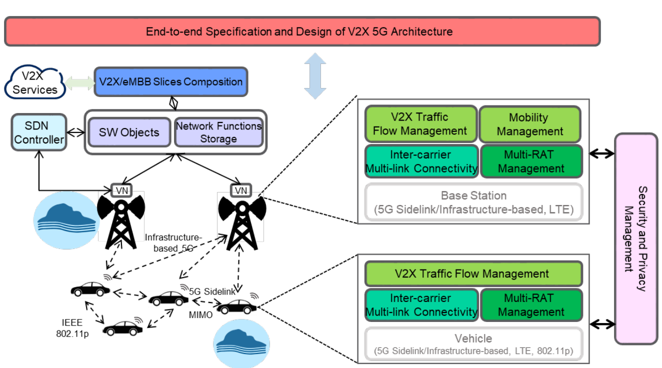


Fig. 6: Fog Computing architecture

Understanding the connected car as a complex cyber-physical system (CPS), many of the communication techniques designed for the Internet of Things (IoT) and fog computing can be applied and adapted to networks supporting connected vehicles. This includes, among others, optimized wireless communication protocols, data formatting protocols, cloud and fog computing, Software-Defined Networking (SDN), Network Function Virtualization (NFV), etc.

Fog computing is a system-level architecture to extend compute, network, and storage capabilities of the cloud to the edge of the network. In the context of fog computing, the SDN paradigm enables a global orchestration of all network resources including the management of distributed fog and cloud domains and the coexistence of heterogeneous networks combining different types of communication technologies. In its turn, NFV has introduced a novel paradigm where services can be deployed on demand in order to fulfill the end user needs. These three techniques (fog computing, SDN, NFV) are intertwined: in future communication networks, services will be deployed over a cloud computing infrastructure, where the necessary connectivity is provided by an SDN controller.

The authors have previously proposed in [16] the usage of a service orchestrator for IoT applications. Under this context, the SDN orchestrator must carry out the following three key functions: i) facilitate the transport of the huge amount of data generated at the terminals, sensors, machines, nodes, etc., to any distributed computing node, edge, or core data center; ii) allocate computing and storage resources in distributed fog nodes and data centers; and iii) process the collected data to make proper decisions, leading to the concept of cognition.

Figure 6 shows the proposed location for fog computing in a connected car environment:

- A fog node could be inserted inside the car, in order to offer the various third party OAM services and applications on top of the same infrastructure (e.g., lane merge, see through, ftp client, video client). This approach would simplify the vehicle control architecture, reduce control system weight and cost of software development.
- Following Multi-access Edge Computing (MEC) architecture, a fog node could be located on the BTS, where RAN information can be accessed in real time. Moreover, this location could allow the allocation of ITS services and applications near the edge of the network in order to provide low-latency.

Beyond connectivity, the ultimate key element here is the data, from which real value can be obtained. In the end, connectivity is just the means to gather and obtain the data. When it comes to processing the data, formatting it becomes a key design decision. Indeed, the adoption of a common, flexible, and powerful data and information modeling language to define all sensors, actuators, gateway facilities and services is a first important step towards the standardisation of IoT frameworks across multiple vendors beyond the existing ones. The automotive sector is not an exception to this.

Among other options, over the last years, YANG [17] has been steadily growing in the IT and networking communities as a data modeling language suitable for the IoT. For such purpose, YANG data models need to be complemented with NETCONF/RESTCONF protocols [18]. These protocols enable the control and management of YANG data models.

VIII. A BUSINESS PERSPECTIVE FOR THE CONNECTED CAR

The automotive market has traditionally had high entry barriers that have been lowered since the adoption of connectivity. Nowadays, connected car is a fast-growing segment owing to the increase of embedded in-vehicle connectivity and smart phone integration platforms.

Car producers are collaborating with the telecommunication sector and other stakeholders to provide more services in connected cars. The introduction of 5G is going to be the major change for business models, enabling new services and improving the existing ones. 5G can bring capabilities such as network slicing, with each slice working in isolation for different types of service. Different slices can separate accounting and billing depending on the properties and reflecting the throughput, latency, and data consumption of the V2X services. As part of the 5GCAR project, we are analyzing the evolution of the automotive sector to point at feasible business models that enable 5G V2X services. To do so, the initial work is to understand the opportunities that can be offered by different actors in the ecosystem.

The automotive sector has typically been an example of a well-defined and specialized value chain. The automotive industry had a linear development going from suppliers of raw materials and basic components to more complex components, vehicle manufacturers, dealers, and lastly the aftermarket sector. However, due to connectivity, the value chain is transforming into a value network. This term refers to having aligned business models, instead of having a chain with each actor giving value from left to right until the end product. Value networks are examples of economic ecosystems, where every node in the network relies on others to create a common value proposition [19].

It is rare for a single company to have every competence required to create a vertical solution with the increasing demands of new technologies and cross-industrial ecosystems. Therefore, cooperation both within and between different sectors is needed. In the ecosystem where vehicles must talk to each other, cooperation to ensure using compatible technologies, including those manufactured by competitors, is fundamental.

In terms of business models for connected cars, one of the key future research lines is on the ways to enable business cooperation and clear value propositions for road safety cases, including the implications on regulation that could encourage the adoption of 5G V2X technologies. One alternative is to leverage on the adoption of infotainment services to amortize the investment cost on safety features, but more alternatives should be examined in order to find feasible business opportunities.

IX. CONCLUSION

We have presented a selected set of topics that are necessary for achieving the 5G connected car. A significant topic are the characteristics of the underlying V2X channels. We have also introduced the main building blocks of a cellular V2X solution. A flexible network architecture has been presented in order to support advanced V2X services. We have also explored the potential of using vehicles in the form of mobile base stations as part of that flexible architecture. Fog computing has been presented in the context of the connected car, and finally a business ecosystem surrounding connected cars has been presented. Further work on these current research topics will allow the fast introduction of the 5G connected car.

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Mikael Fallgren is a Senior Researcher at Ericsson Research, Stockholm, Sweden. He has received a M.Sc. degree in engineering physics and a Ph.D. degree in applied and computational mathematics from KTH (the Royal Institute of Technology), Stockholm, and a B.Sc. degree in business administration from Stockholm University. His research interests include V2X and wireless access networks. In the METIS project he led the work on scenarios and requirements as well as on dissemination and standardization. He was editor for two chapters of the book: 5G Mobile and wireless communications technology. Dr Fallgren is the 5GCAR project coordinator.

Markus Dillinger received his Diplom-Ing. degree in telecommunications in 1990 from the University of Kaiserslautern, Germany. In 1991 he joined the Mobile Network Division at Siemens for development of GSM base stations. From 1995 on, he was working on the definition of the third mobile radio generation in the European research projects. From 2000 he led Software Defined Radio research activities within the Siemens network division. He was leading several EU research programmes. From 2005 onwards he was director for mobile broadband solutions and later for enterprise solutions. In 2010 he joined Huawei Germany and was director for enterprise solutions for smart grid. In 2013 he has joined Huawei European Research Centre as Head of Wireless Internet Technologies where he runs private and public R&D programmes for e.g. car-to-car and automation supporting 3GPP standardization and normative work for the vertical industry.

Jesus Alonso-Zarate , PhD, MBA, and IEEE Senior Member is now Senior Researcher, Head of the M2M Communications Department, and Manager of the Communications Technologies Division at CTTC in Barcelona. Since 2010, he has published more than 140 peer-reviewed scientific papers in the area of M2M communications and the Internet of Things. He has received various best paper awards in prestigious conferences and journals. He is very active in internationally collaborative R&D projects funded by the European Commission, the European Space Agency (ESA), and also the Spanish Government, being principal investigator in some of them. In addition, he is involved in research and technology transfer projects with industry. From April 2015 to March 2017, he served as Editor-in-Chief of the European Alliance for Innovation (EAI) Endorsed Transactions on the Internet of Things (IoT). In addition, he is part of the Editorial Board of the IET Wireless Sensor Systems Journal and the Wiley Transactions on Emerging Telecommunication Technologies (ETT). Over the last 5 years, he has given more than 50 invited talks and tutorials in international events. More info at www.jesusalonsozarate.com.

Mate Boban is a Principal Research Engineer at Huawei German Research Center, Munich. He earned his diploma in Informatics from University of Zagreb and his Ph.D. degree in electrical and computer engineering from Carnegie Mellon University. Before joining Huawei, he worked for NEC Labs Europe, Carnegie Mellon University, and Apple. He is an alumnus of the Fulbright Scholar Program. He has co-chaired several IEEE workshops and conferences and has been involved in EU-funded projects on V2X communication (WP leader in DRIVE-C2X and TEAM, 5G CAR). He actively participates in 5GAA, ETSI, and 3GPP. His current research is in the areas of channel modeling and cross-layer protocol design for V2X communication systems. For his work on V2X, he received the Best Paper Awards at the IEEE VTC Spring 2014 and at IEEE VNC 2014. More information can be found at http://mateboban.net.

Taimoor Abbas (S09, M14) is a project leader for 5G and V2X development at Volvo Car Corporation. He earned his Ph.D. degree in radio systems and M.Sc degree in wireless communications from the department of Electrical and Information Technology, Lund University in 2014 and 2009, his M.Sc. degree in electronics from Quaid-i-Azam University Islamabad in 2006, respectively. His research interest include cooperative Intelligent transportation, multi-antenna and 5G systems as well as the estimation and modeling of radio channels for wireless vehicular communications. He received the Best Paper Awards for his work on V2V, at the IEEE ITST 2013, IEEE WIVEC 2013 and ACEEE-ICT 2011.

Konstantinos Manolakis is a Senior Research Engineer at the Huawei Munich Research Center since 2014. Prior to that, he was a Research Associate at the Technische Universitt Berlin (2012 - 2014), whereas from late 2006 to 2012 he was with the Fraunhofer Heinrich Hertz Institute in Berlin, Germany. Dr. Manolakis holds a Ph.D. (Dr.-Ing.) and a M.Sc. degree in wireless communications from the Technische Universitt Berlin, and a Diploma degree in electrical engineering from the Aristotle University of Thessaloniki in Greece. He has participated at several projects funded by the German government and the European Union in various roles, as well as to industrial research projects and standardization activities. His main expertise covers radio transmission and access technologies, physical layer design and signal processing, while more recently he has been focusing on vehicular communication and its integration into 5G networks. Dr. Manolakis has co-authored more than 30 peer-reviewed journal, magazine and conference papers, which have received more than 700 citations, and has been the main recipient of the Best Paper Award at the 77th IEEE Vehicular Technology Conference (VTC) in 2013.

Toktam Mahmoodi received the B.Sc. degree in electrical engineering from the Sharif University of Technology, Iran, and the Ph.D. degree in telecommunications from Kings College London, U.K. She was a Visiting Research Scientist with F5 Networks, San Jose, CA, in 2013, a Post-Doctoral Research Associate with the ISN Research Group, Electrical and Electronic Engineering Department, Imperial College from 2010 to 2011, and a Mobile VCE Researcher from 2006 to 2009. She worked on European FP7 and EPSRC projects shaping mobile and wireless communication networks. She has also worked in mobile and personal communications industry from 2002 to 2006, and in an R&D team on developing DECT standard for WLL applications. She is currently with the academic faculty of Centre for Telecommunications Research at the Department of Informatics, Kings College London. Her current research interest include 5G communications, network virtualization, and low latency networking.

Tommy Svensson [S98, M03, SM10] is Professor in Communication Systems at Chalmers University of Technology in Gothenburg, Sweden, where he is leading the Wireless Systems research on air interface and wireless backhaul networking technologies for future wireless systems. He received a Ph.D. in Information theory from Chalmers in 2003, and he has worked at Ericsson AB with core networks, radio access networks, and microwave transmission products. He was involved in the European WINNER and ARTIST4G projects that made important contributions to the 3GPP LTE standards, the EU FP7 METIS and the EU H2020 5GPPP mmMAGIC 5G projects, and currently in the EU H2020 5GPPP 5GCar project, as well as in the ChaseOn antenna systems excellence center at Chalmers targeting mm-wave solutions for 5G access, backhaul and V2X scenarios. His main research interests are in design and analysis of physical layer algorithms, multiple access, resource allocation, cooperative systems, moving networks and satellite networks. He has co-authored three books, 63 journal papers, 114 conference papers and 49 public EU projects deliverables. He is Chairman of the IEEE Sweden joint Vehicular Technology/ Communications/ Information Theory Societies chapter, has served as editor of IEEE Wireless Communications Letters and as coordinator of the Communication Engineering Master's Program at Chalmers.

Andres Laya is Experience Researcher at Ericsson Research, Stockholm, Sweden. He holds an M.Sc. degree in ICT from BarcelonaTECH (UPC), Spain. He received a Ph.D. in communication services and infrastructures from KTH, Sweden. He has been involved in Swedish and European projects together with Ericsson, Nokia, Orange, Telecom Italia, Sony Mobile, and Aalto University in subjects related to machine type communications. His research interests are in the area of the Internet of Things, and the business implications of connected devices in different industries.

Ricard Vilalta (SM17) has a telecommunications engineering degree (2007) and Ph.D. degree (2013), at UPC, Spain. He is senior researcher at CTTC, in the Communication Networks Division. He is currently a Research Associate at Open Networking Foundation. His research is focused on SDN/NFV, Network Virtualization and Network Orchestration. He has been involved in international, EU, national and industrial research projects, and published more than 170 journals, book chapters, conference papers and invited talks.